Anthropogenic warming has substantially increased the likelihood of July 2017-like heat waves over Central-Eastern China

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ANTHROPOGENIC WARMING HAS SUBSTANTIALLY INCREASED THE LIKELIHOOD OF JULY 2017–LIKE HEAT WAVES OVER CENTRAL EASTERN CHINA

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Heat waves in central eastern China like the record-breaking July 2017 event were rare in natural worlds but have now become approximately 1-in-5-yr events due to anthropogenic forcings.

INTRODUCTION. During July 2017, an unprecedentedly intense heat wave struck central eastern China, resulting in drastically increased human morbidity/mortality, steeply reduced agriculture productivity, and serious shortage of electricity and water supply (CMA 2017). Many meteorological stations registered 15–25 hot days (daily maximum temperature over 35°C), and some even had record-high July temperatures, such as a new record of 40.9°C among historical observations since 1873 at Xu-Jia-Hui station in Shanghai (CMA 2017). The China Meteorological Administration issued 10 high-level warnings against hot weather during 21–25 July. Such unprecedentedly frequent alarms within only 5 days attracted intense scrutiny from policy-makers, media, and the public on the relationship between this heat wave and global warming.

Previous studies usually conducted attribution analyses on seasonal warmth in central eastern China (e.g., the 2013 record-breaking summer; Sun et al. 2014), leaving attribution statements for short-term (synoptic) hot extremes sparsely reported. This study therefore attempts to answer whether and to what extent anthropogenic warming has increased the likelihood of 5-day heat waves as hot as or hotter than the 21–25 July 2017 case over central eastern China.

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DATA AND METHODS. Homogenized observations of daily maximum temperatures (Tmax) during 1960–2017 from 760 meteorological stations are used [Li et al. 2015; for homogenization methods see Szentimrey (1999)]. Daily observations is interpolated onto the 0.56° × 0.83° grid of the model via a "natural neighbor" scheme (Sibson 1981), following the model's resolution and geography.

The upgraded HadGEM3-GA6-N216 model is employed (Christidis et al. 2013; Ciavarella et al. 2018). Model outputs include all-forced simulations conditioned on the observed 2017 sea surface temperature (SST) and sea ice from the HadISST dataset (Rayner et al. 2003) and naturalized simulations with anthropogenic signals removed from observed SSTs and with preindustrial forcings. Accordingly, occurrence probabilities and resultant attribution conclusions reported in this study are also conditioned on the 2017 SST patterns. The ensemble is generated through physics perturbations of multiple initial conditions with identical external forcings.

More specifically, historical simulations (histCLIM) consisting of 15 members over 1961–2013 are compared with interpolated observations to evaluate the model's fidelity in simulating climatological statistics (mean and variability) of the strongest 5-day heat waves. Two ensembles of 525-member simulations for the 2017 July with (hereafter histALL, as an extension of previous histCLIM runs) and without (hereafter histNAT) anthropogenic forcings are used to estimate the probability of the 21–25 July heat wave in each scenario. Denoting P_{ALL} and P_{NAT} as the occurrence probability of events equivalent to or stronger than the targeted case in 525-member histALL and histNAT ensembles, the risk ratio (RR) is expressed as $P_{\mathrm{ALL}}/P_{\mathrm{NAT}}$. The fraction of attributable risks (FAR) is expressed as $1 - P_{\mathrm{NAT}}/P_{\mathrm{ALL}}$.

Reference climatologies over 1961–90 are formed for both simulations (ensemble mean of 15-member histCLIM) and observations from the hottest 5-day running mean Tmax in July. These pentad climatologies are approximately 2°–3°C warmer than July monthly-mean Tmax climatologies in both simulations and observations, and serve to distinguish especially intense 5-day heat waves from more typical 5-day cases (Figs. 1c,d). Respective climatologies are then removed from observations and simulations to create overlapping pentad Tmax anomalies (hereafter PTmax; see Fig. 1c). Based on these PTmax anomalies, both the historical distribution of the hottest 5-day heat waves and warm anomalies for the 2017 case could be well reproduced by this model (see Fig. ES1 in the online supplemental information), indicating the suitability of using this model and PTmax anomalies for attributing this 5-day heat wave. Freychet et al. (2018) also reported good performance of this model in simulating characteristics of 5-day heat waves in

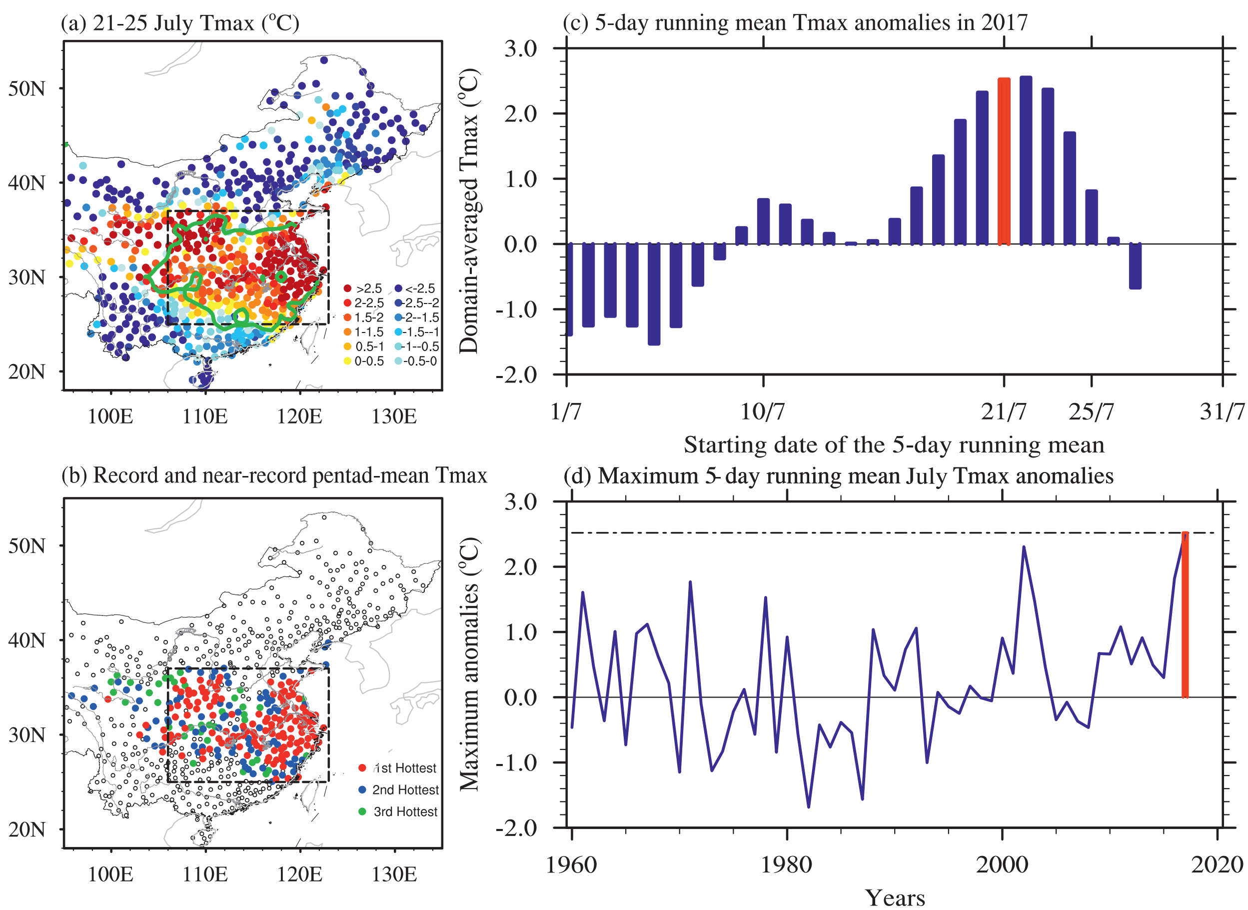

Fig. 1. (a) Observed pentad-mean (21–25 Jul 2017) Tmax anomalies (°C) relative to the 1961–90 climatology for the maximum 5-day mean Tmax. The green contour indicates the 35°C-isoline of mean Tmax during this pentad. Central eastern China is shown by the dashed rectangle. (b) Spatial distribution of stations that registered record- and near-record (since 1960) pentad-mean July Tmax during 21–25 Jul 2017. (c) Observed overlapping pentad-mean Tmax anomaly averaged over central eastern China during July 2017. Each value is indexed by the first day of the pentad. (d) Observed maximum 5-day mean Tmax anomaly averaged over central eastern China in each July over 1960–2017. The red vertical line labels the 2017 event, and the dashed line indicates its anomaly.

central eastern China, as it is capable of capturing critical mechanisms generating heat waves there. In the reminder of this paper, we used the PTmax anomaly to define the threshold.

RESULTS. During 21–25 July, almost the entirety of central eastern China had temperatures over 35°C, equivalent to 2°–6°C PTmax anomalies (Fig. 1a). Anomalies of these magnitudes produced numerous record- or near-record July PTmax (Fig. 1b). In terms of domain-averaged values, the PTmax in this pentad not only peaked during July 2017, but also set a new record among all historical July counterparts (any 5-day mean Tmax during July) since 1960 (Figs. 1c,d; note that we consider this pentad instead of 22–26 July because of its extensive social and economic repercussions). It is well known that heat waves in this area result dynamically from the persistence of anticyclonic circulations that facilitate increased surface solar radiation and adiabatic heating (Freychet et al. 2017; Chen and Lu 2015). Specific to this case, an unprecedentedly (all Julys since 1960) strong anomalous anticyclonic cell was centered above central eastern China, dynamically explaining the origin of the "record-breaking" Tmax (Fig. ES2) and its exclusive occurrence in this domain (Fig. 1a).

The PTmax anomaly from the interpolated observation (2.52°C) was used as a threshold to characterize the July 2017–like heat wave. Events of this magnitude are fairly rare (P_{NAT} = 2.1%) in natural-forcing simulations (Fig. 2a, green). Without anthropogenic warming, similar heat waves should have been seen one to three times per century [mean return period: 47.7 yr; 95% confidence interval (CI): 30.8–75.0 yr; Fig. 2b, green]. By contrast, the distribution of simulated PTmax anomaly is markedly positive-displaced in all-forcing worlds, signifying substantially increased odds (P_{ALL} = 20.1%) of events this hot. In the current climate, anthropogenic warming has exposed central eastern China to 2017-like heat waves about twice per decade (mean return period: 4.9 yr; 95% CI: 4.3–5.8 yr; Fig. 2b, red).

Quantitatively speaking, the risk of an event as hot or hotter increased at least tenfold (RR = 9.8; 95% CI: 5.9–18.9) due to anthropogenic warming. Translating into FAR, human influence accounted for at least 90% (95% CI: 83.0%–94.7%) for the presence of 2017-like heat waves. To avoid selection bias potentially introduced by using the critical threshold at the very end tail (Stott et al. 2004), we also adopted the second hottest July record (2.09°C in July 2002) as an alternative threshold. Simulated anomalies

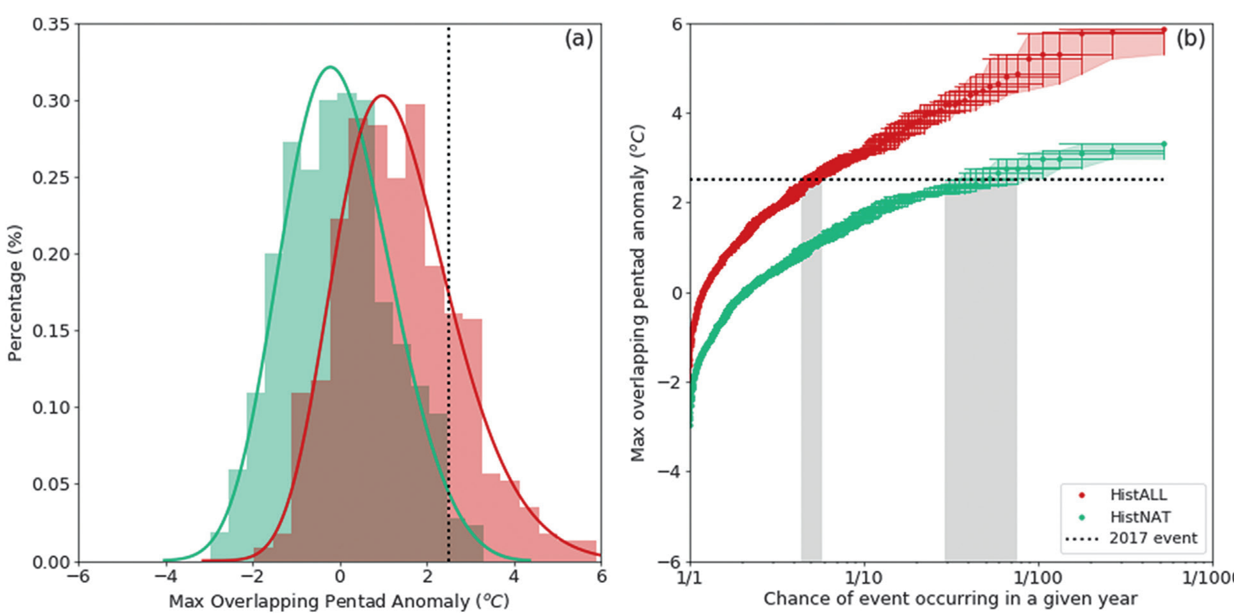

Fig. 2. (a) Distribution of domain-averaged hottest 5-day mean Tmax anomalies during July 2017 (histogram), based on 525-member histALL (red) and histNAT (green) ensembles, and their generalized extreme value (GEV)-fitted curves shown by respective colors. (b) Return periods of domain-averaged hottest 5-day mean Tmax anomalies in histALL (red) and histNAT (green) ensembles. The threshold value of 2.52°C is indicated by dashed lines in (a) and (b). In (b), vertical and horizontal bars represent the 5%–95% uncertainty interval of temperature anomalies and return periods, derived via the bootstrapping method (*N* = 1000). Gray shadings specify the uncertainty interval of return period of the threshold exceedance in histNAT and histAll runs.

exceeding this threshold are recorded 5 times more frequently (RR = 4.5; 95% CI: 3.4–6.5) in the all-forcing world (P_{ALL} = 26.8%) than in the natural-forcing world (P_{NAT} = 5.9%). These results also indicate that anthropogenic forcings contributed more to increases in the risks of rarer, more extreme heat waves. So, we reiterate that anthropogenic warming played an overarching role (FAR = 77.8%; 95% CI: 70.4%–84.6%) in elevating the risk of heat waves stronger than this second-hottest threshold (e.g., the July 2017 case).

CONCLUSIONS AND DISCUSSION. In central eastern China, heat waves hotter than the July 2017 event should have had a very slim chance to occur in natural-forcing worlds. But now, forced by anthropogenic warming and conditioned on the 2017 SST pattern, a 5-day heat wave like this case has become 10 times more likely, as a 1-in-5-yr or more common event.

Although influences of anthropogenic warming could be detected and were largely attributable, attribution conclusions for a single high-impact case may be subject to some uncertainties. First, the estimated RR and FAR may be quantitatively sensitive to the selection of baseline periods (here 1961–90), as reported by Knutson et al. (2013). Still, sensitivity tests adopting varying baselines for this case indicate that the qualitative statement "increase in the likelihood of a July 2017–like heat wave could be largely attributable to anthropogenic warming" robustly holds. Second, the estimated RR and FAR only apply to the current climate. As the planet keeps warming, a higher RR of a July 2017-like case would be expected (Perkins and Gibson 2015). Future reductions in aerosols due to increasingly stricter air quality control in this area may also give a greater RR of a July 2017-like case (van Oldenborgh et al. 2018; Wang et al. 2018). This study is based only on factual and counterfactual runs in a single atmosphere-only model, with the intention of exploiting its large ensembles for calculating the statistics of rare events (Otto 2017). Estimated RRs should still be compared with those derived via other methods/models, such as observation-constrained estimates (van Oldenborgh et al. 2015), alternative atmosphere-only model-based estimates (e.g., weather@home; Massey et al. 2015), and fully coupled model-based estimates (CMIP5; Sun et al. 2014) to further clarify uncertainties.

Comparing temperatures alone in factual and counterfactual simulations, the estimated RR only delivers a general attribution message, leaving physical interpretations about how anthropogenic forcings influenced the likelihood of the heat wave and its preferential occurrence in central eastern China to be addressed. To this end, follow-up efforts will be made to disentangle this general attribution effort into a dynamic (e.g., large-scale circulations) and a thermodynamic part (Vautard et al. 2016; Schaller et al. 2016). A critical step toward dynamic attribution is to quantify the extent to which anthropogenic warming affected the presence, location, maintenance, and amplitude of anticyclonic circulations akin to the 2017 case (Fig. ES2). Such a separation could also facilitate tracking down and communicating the source of attribution uncertainties from both dynamic and thermodynamic perspectives (Vautard et al. 2016; Wehrli et al. 2018).

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